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DIGITAL DISPLAY OF ASTRONOMICAL DATA

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A brief summary is given of techniques to enhance for photographic display digital astronomical images. The phenomenon of "photographic de-resolution" is discussed and a proposed algorithm (the "highpass squared" filter) is presented to correct for this effect.

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Introduction

Much of modern astronomy involves imaging of areas on the sky. Thus a large fraction of an astronomer's time can be spent doing "image processing." Astronomical imaging and image processing have been revolutionized in recent years by digital techniques: imagery is now routinely obtained with digital detectors such as charge-coupled device (CCD) arrays and imagery originally obtained on photographic plates can now be digitally manipulated through the use of digitizing microphotometers. Digital imagery is now even available at radio wavelengths from interferometric arrays.

In any case, displaying the digital image in a humanly viewable form, after all the processing, reconstruction, filtering, mapping, measuring, analysis etc. is complete, is an important goal of the image analyst. However, looking at an image after it has been transferred to a photograph can be quite different than looking at the same image on a computer display. Both the logarithmic nature of film and the limited number of distinguishable gray-levels cause a loss of information in the transfer from computer to photograph. Thus it becomes a goal of the image analyst to minimize this loss of information, or more likely, to tailor the transfer from computer to film to emphasize "useful" information at the expense of "not-so-useful" information.

Put more simply, after the astronomer as image analyst has completed his quantitative analysis of an image at the computer display terminal, and studied such image representations as contour maps and the like, he must decide how to display the image on a photographic print (to accompany his journal paper) in the best possible way. He usually will endeavor to make a photograph that qualitatively emphasizes certain "interesting" aspects of the image. For lack of a better term, let us call this exercise "display enhancement."

Techniques of Display Enhancement

There are several well known techniques that can be used for display enhancement (see, for example, R.C. Gonzalez and P. Wintz, Digital Image Processing, 1977, Addison-Wesley). One procedure is usually called "histogram modification" which involves transforming an image to better match the available range of gray-levels in a photographic print. Usually, the histogram modification transform is performed such that each gray-level covers an equal amount of area on the print. Thus an image with a narrow spread of intensities can be transformed such that these intensities are spread over the complete set of gray-levels. Or, in a more subtle use of the technique, a narrow range of intensities may be expanded, and thus emphasized, at the expense of less informative intensity ranges. An analog form of histogram modification is obtained by printing a negative through a low contrast mask.

One impressive technique of display enhancement is the construction of a so called "pseudo-color image" where a given color represents a range in intensity. Thus, what is basically a contour map is transformed into a colorful image. Unfortunately, the cost of publishing or distributing color photographs is still prohibitive and the advantage of pseudo-color images over contour maps is controversial.

A frequent complaint about photographic versions of digital images is a lack of "sharpness." Thus, a common technique of display enhancement is edge emphasis. Such enhancement may take the form of highpass filtering to attenuate the background relative to the high frequency "edges." A combination of highpass filtering and histogram modification can dramatically reveal fine detail in highlights that are usually "burnt-in" by conventional photographic reproductions (see, for example, M.S. Burkhead and W. Matuska 1980, A.A.S. Photo-Bulletin, 23, 13). An analog form of high pass filtering plus histogram modification is obtained by printing a negative through an "unsharp mask" (D.F. Malin 1977, A.A.S. Photo-Bulletin, 16, 10).

Another approach to sharpening an image is to incorporate into the displayed image some gradient information: a pixel may be replaced by a certain gray-level when the gradient of the image at that pixel exceeds a certain threshold.

Yet another way of sharpening a displayed image is to utilize a digital analog of the "edge effect" inherent in photographic developers (especially viscous developers). (See H. Liff and B. Rudomen 1980, Proc. SPIE, 249, 100). These edge effects produce sharper and subjectively more pleasing images by overemphasizing edges between light and dark regions (thus applying a form of highpass filtering) and allowing narrow "pulses" to be separated more cleanly. Applying a suitable adaptive, non-linear Liff-Rudomen filter to a density-transformed digital image can controllably mimic the use of a viscous developer and appreciably enhance the subsequent photographic print.

Photographic De-Resolution of Digital Images

There is one effect involved in the transfer of digital images to film that is very important in astronomical applications and is not adequately treated by the previously described display enhancement techniques such as highpass filtering. Consider an image of a group of astronomical objects. The light distribution as seen from the earth from an unresolved star or an unresolved piece of a larger source has a Gaussian profile caused by atmospheric degradation or "seeing." A digital detector records the collection of Gaussian light profiles from the objects observed and, after further reduction, an image of these stars is written onto film for hard-copy display. However, since photographic film is a logarithmic rather than a linear detector, a Gaussian intensity profile written onto film with a Gaussian shaped spot will <u>not</u> appear on the resulting photograph as a Gaussian shaped density image but rather as a much "fatter" image. Not only is the resulting density image not the expected Gaussian, but the actual resolution of the image (as expressed by the full-width at half-maximum or FWHM) is degraded, thus exacerbating the effects of image overlap and preventing the resolution of faint objects situated near bright objects. We call this effect "photographic de-resolution."

A simple, idealized, calculation illustrates this problem in more detail. Assume that a typically observed stellar Gaussian seeing image covers a range of 100 in intensity (I) and assume that the density (D) on the photograph can be expressed as $D = \log I$ (in other words, $\gamma = 1$). Thus the range in D seen on the photograph is 2. Therefore, if the Gaussian intensity profile is $I(x) = 100 \exp[-0.5(x/\sigma)^2]$ (where x is in arcseconds and σ describes the width of the seeing disk in arcseconds), then $D(x) = 2 + \log(\exp[-0.5(x/\sigma)^2] = 2 - 0.217(x/\sigma)^2$. The FWHM of these distributions can be determined by expressing the values of x (in terms of σ) where the profile falls to half its maximum value. Thus $x_{I=50} = 1.18\sigma$ while $x_{D=1} = 2.15\sigma$ and we find that the effect of writing a digital image onto a photograph results in an increase in the FWHM of the seeing profile by a factor of 1.8.

Obviously, the astronomer as image analyst will sometimes need a display enhancement tool to correct, at least qualitatively, for photographic de-resolution. One attractive approach would be to derive an optimum filter to convolve with the highlights in an image to "sharpen" the intensity Gaussians so as to produce Gaussian density profiles when the entire image is converted into density. Or, it might seem reasonable to take an analog approach by modifying the shape of the light-spot used to write the image onto film such that the resulting density spot is Gaussian. Unfortunately, such a filter or modified light-spot is appropriate only for Gaussian intensity images of one specified height. Images which are brighter or fainter would not be transformed into Gaussians in density. Thus, for this reason, and since it is only appropriate to apply such a sharpening filter to the highlights of an image, an adaptive filter must be used that has a different effect from pixel to pixel in the image.

A suitable adaptive algorithm might be constructed to identify the unresolved peaks in an image and sharpen them by a tapered normalization (such that the peak intensity stays the same and the filtered portion of a profile smoothly blends with the unfiltered portion). Two problems immediately arise with the implementation of this filter. First, the location of these unresolved peaks is not a trivial task. Second, linear features that are resolved in one direction (for example, a galactic spiral arm) will not be enhanced.

The Liff-Rudomen adaptive filter--perhaps applied recursively--might be a suitable qualitative cure for photographic de-resolution that avoids the pitfalls of a direct profile sharpening filter. As described above, the Liff-Rudomen filter will enhance linear features (since they represent edges) and, at least partially, will sharpen unresolved "pulses" typical of Gaussian shaped seeing disks. Yet, the Liff-Rudomen technique is at best an indirect solution to the problem: the filter was designed to mimic viscous developers not to directly cure photographic de-resolution or lack of sharpness. Also, in practice, the results of Liff-Rudomen filtering are quite sensitive to free parameters and thus many experiments must be performed to arrive at a suitable photograph.

The Highpass-Squared Display Enhancement Algorithm

We have decided to implement a much simpler display enhancement algorithm than any of the ones described above. Our algorithm, which we call the highpass-squared filter, also exhibits the following interesting aspects. Highlights (including unresolved pulses and edges) are qualitatively enhanced and qualitatively sharpened; the enhancements are smooth (which eliminates obvious artifacts around the highlights); and the filter is easy to apply.

The highpass-squared filter consists of the following basic steps. First, the original intensity image is convolved in image space (via the well known moving-box technique) with a Gaussian filter function. Second, the smoothed image is subtracted from the original image and all pixels with negative values are set to zero. The resulting image (which we call the highlight image) contains only the most intense portions of the image and represents the result of a qualitative highpass filter. Third, the highlight image is squared and then renormalized (divided by a constant). Finally, the squared image is added to the original image.

The end result of the highpass-squared algorithm is an adaptive enhancment of the highlights in the image as well as an adaptive sharpening of these same highlights. All the highlights now have a sharp narrow tip superimposed on their profiles that will dominate the density profile when the filtered image is displayed on a photograph. Note also that these sharp tips merge relatively smoothly into the original profiles since the smallest intensities in both the highlight and squared images are just above zero.

There are several obvious places where the highpass-squared algorithm is parameterized. First, the width of the Gaussian smoothing function must be specified. Presumably, this parameter is determined from the scale of the image and from the width of the seeing disk. Second, the level at which points are thrown away from the highlight image may be raised or lowered from zero (however, the highlight image should then be re-biased so the pixels with the smallest intesnsity are set just above zero). These first two parameters will obviously interact. Third, the renormalization parameter for the squared image must be specified. We use as an initial value a parameter such that the original and squared profiles of the most intense highlight in the image are equal. Thus, in the resulting image, the most intense highlight is enhanced by a factor of two in terms of intensity.

Example of the Highlight-Squared Algorithm

In figures 1 through 3 we present three versions of an image of an anonymous galaxy. The original image was obtained by W. Romanishin with the 4-meter telescope of the Kitt Peak National Observatory (KPNO) using a IIIaJ photographic plate exposed through a GG385 filter. The image was digitized with a PDS scanning microdensitometer operated by KPNO. Each pixel in the digitized image represents 1.855 arcseconds on the sky and pixels are separated by half this amount. Figure 1 shows a representation of the original digitized image. Ten gray levels are present (coded by dot density) and the gray levels are equally spaced in log(intensity) to mimic photographic reproduction. Note the general "blandness" of the displayed image: very few highlights (with the prominent exception of the nucleus) appear above the general galactic background.

Figure 2 represents a highlight image of the galaxy (also shown with logarithmic gray-levels). The original image was convolved with a Gaussian profile with FWHM = 5 pixels which was expressed as a 7 x 7 pixel moving box. The smeared image was subtracted from the original image and all negative values were thrown away. Clearly, only the highlights remain. Note that many of these highlights are not visible in figure 1.

The highlight image was squared, renormalized as described in the last section, and added to the original image. Figure 3 is the resulting "final" image (displayed with the same logarithmic gray levels as figure 1). Obviously, the highlights are enhanced (note the spiral arm features on either side of the nucleus) and closely spaced foreground stars (such as the pair at the top center of the image) are clearly resolved into separate peaks).

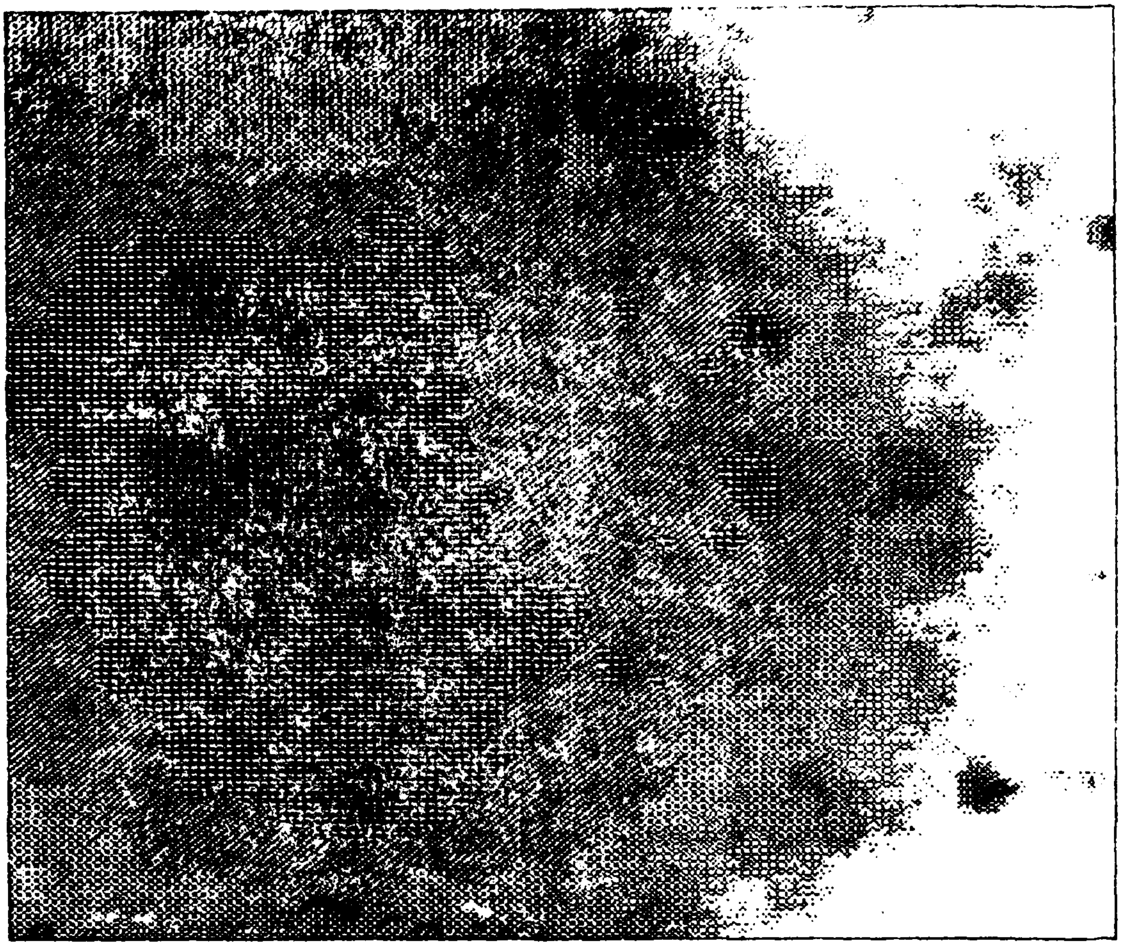

Figure 1. Original image of galaxy.

Figure 2. Highlight image of galaxy.

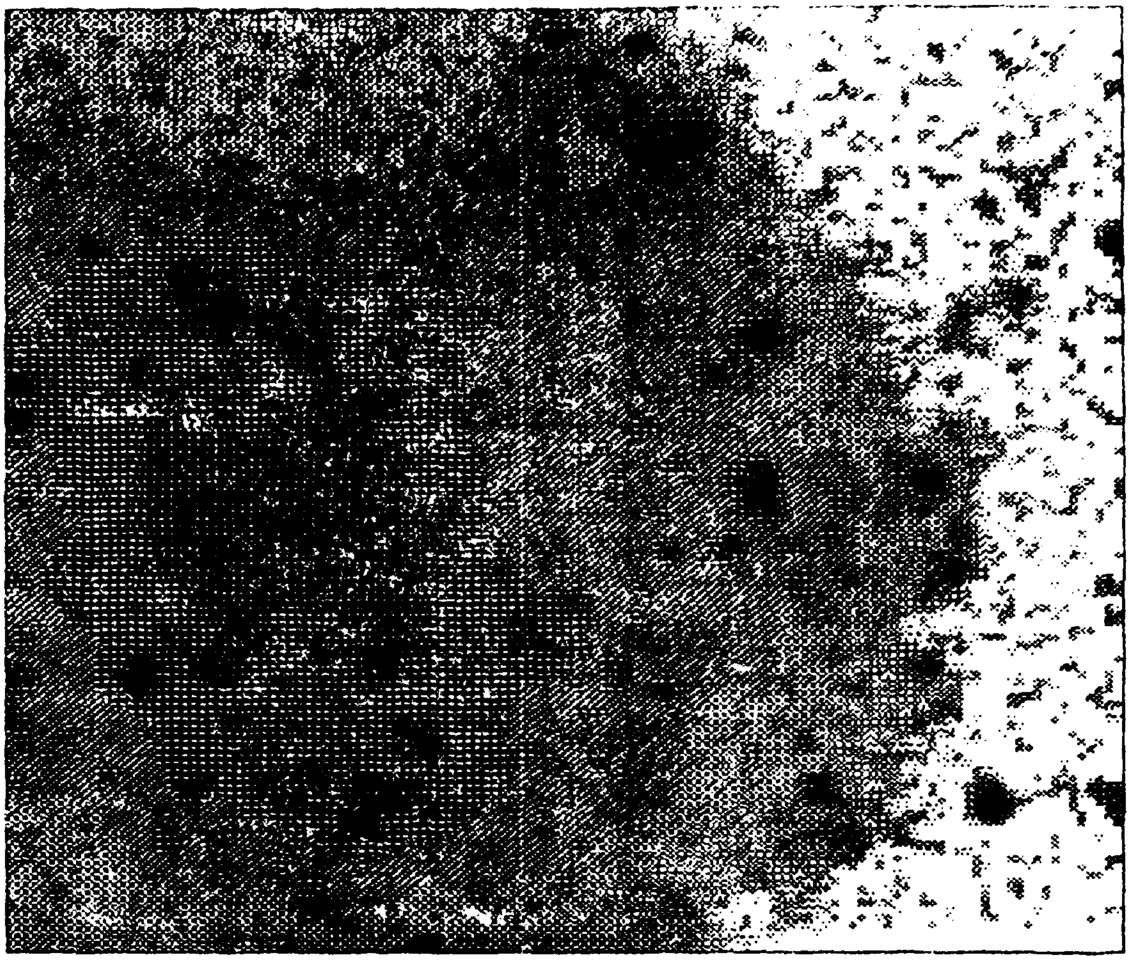

Figure 3. Final image of galaxy.